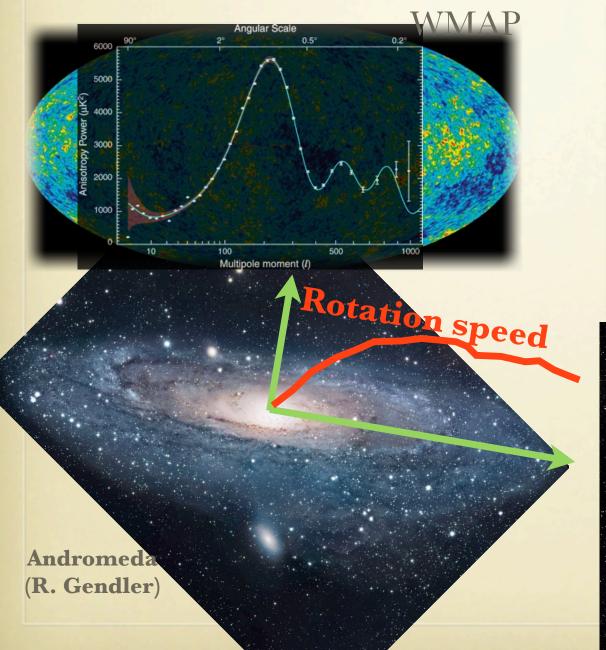


DARK MATTER FROM LARGE TO SMALL SCALES

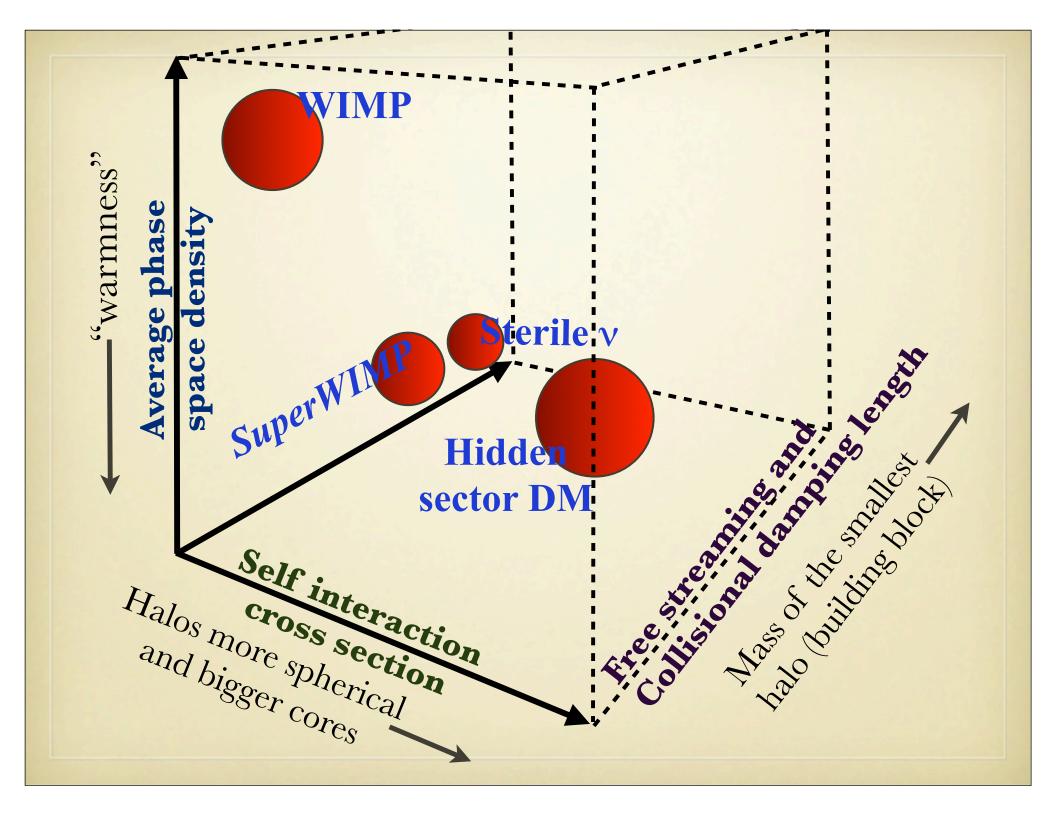


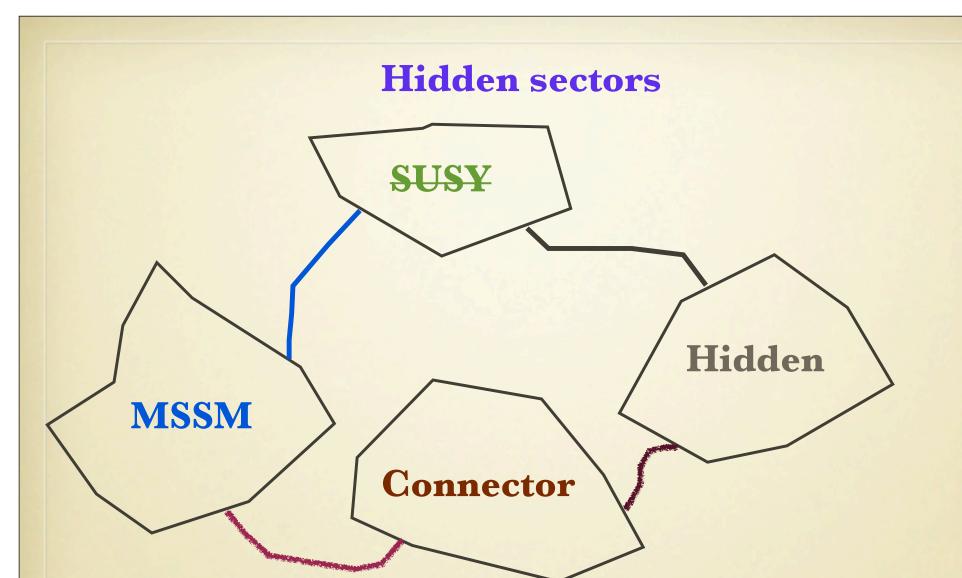




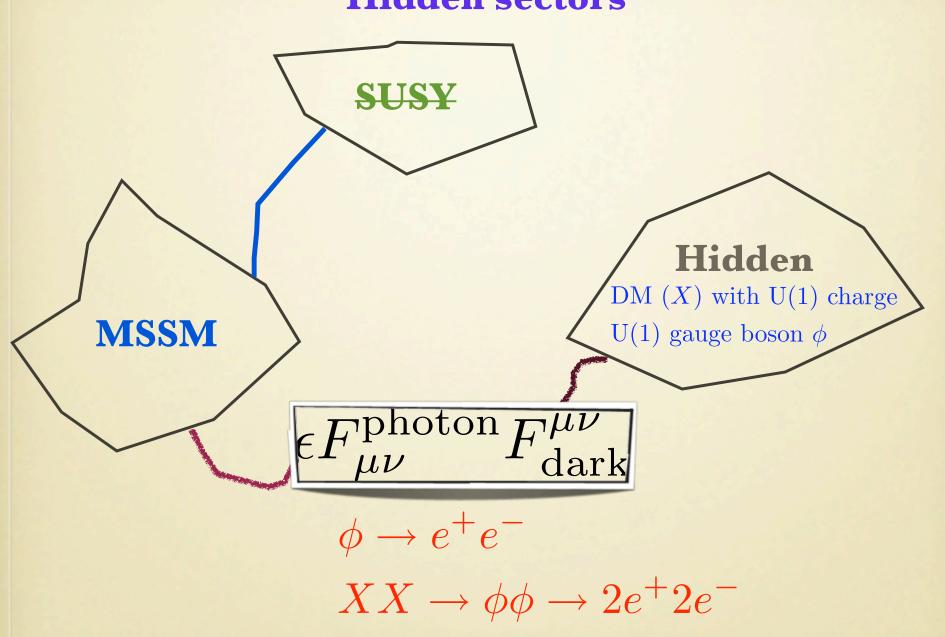
OUTLINE

- Self-annihilations, Self-interactions and PAMELA and Fermi excesses
- Early universe consistency conditions
- The Milky Way satellites
- Cores in nearby galaxies

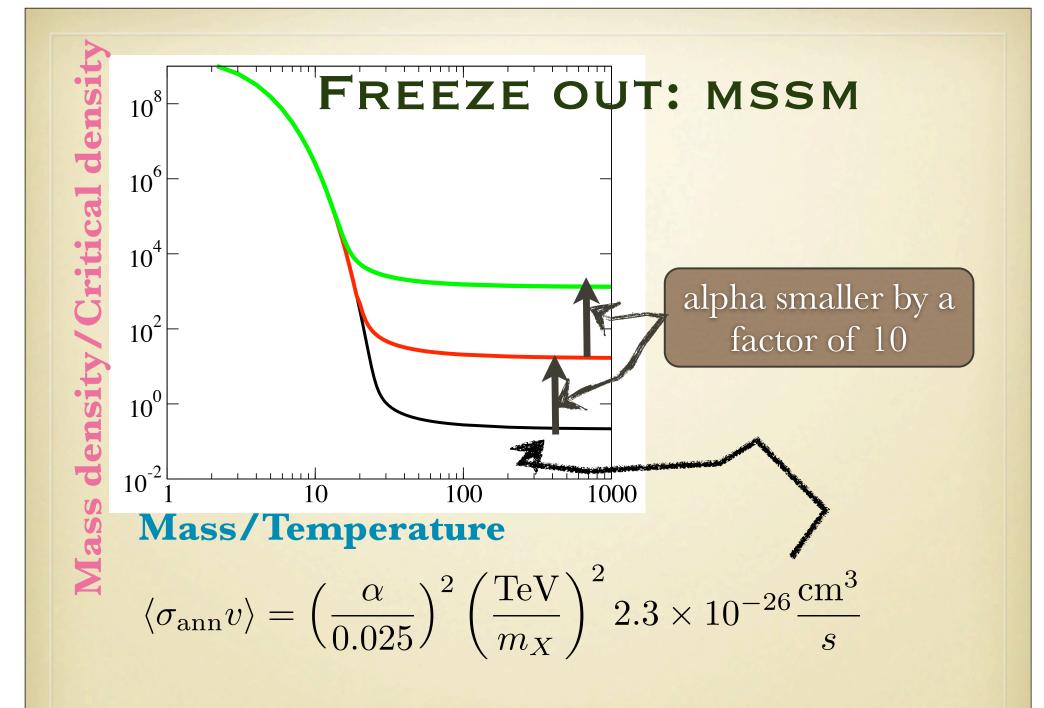


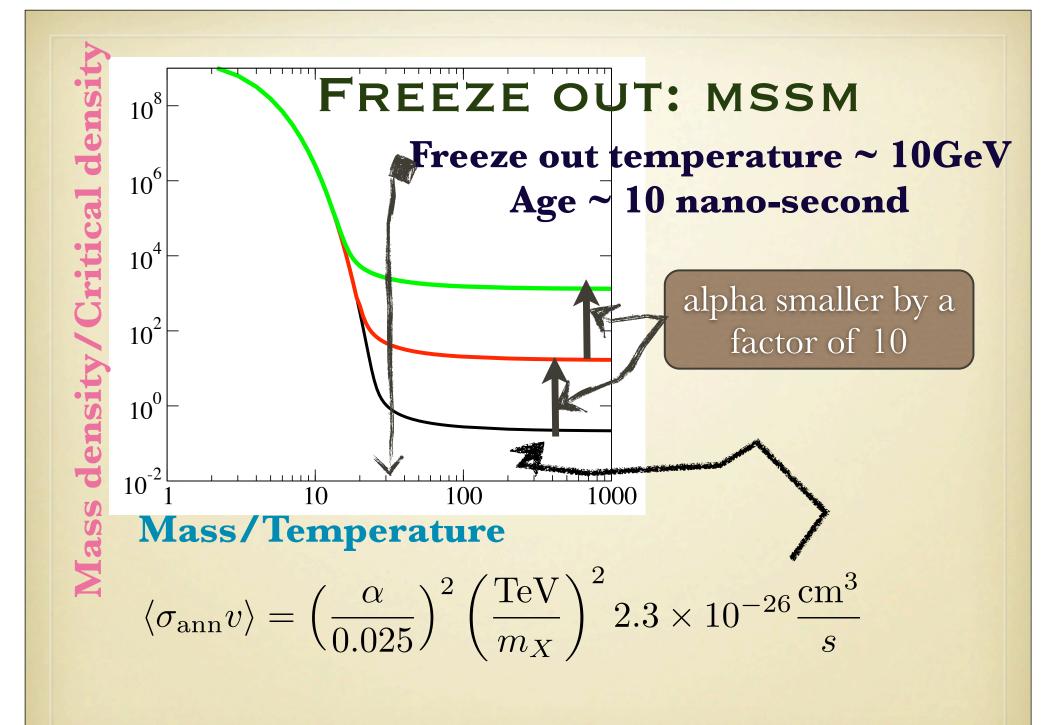


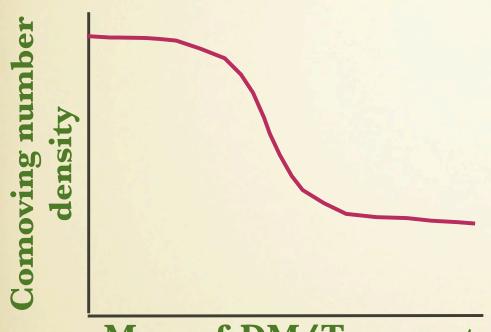




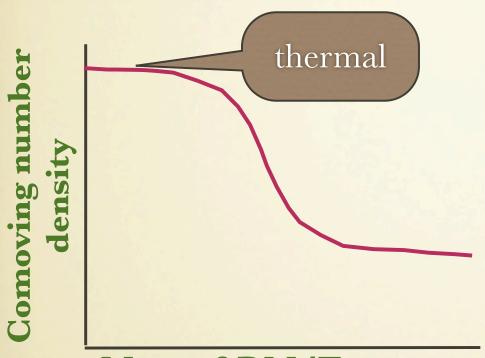
FREEZE OUT: MSSM Mass density/Critical densi 10⁸ 10^6 10⁴ 10^2 10^0 1000 100 Mass/Temperature $\langle \sigma_{\rm ann} v \rangle = \left(\frac{\alpha}{0.025}\right)^2 \left(\frac{\text{TeV}}{m_X}\right)^2 2.3 \times 10^{-26} \frac{\text{cm}^3}{s}$



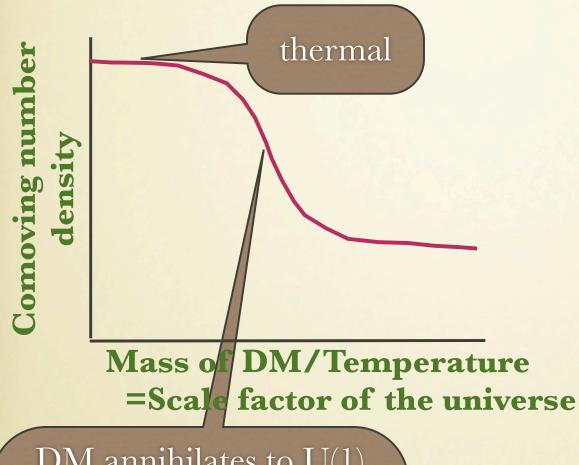




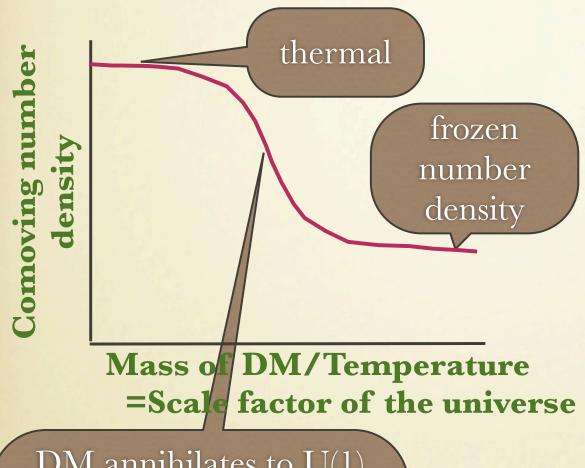
Mass of DM/Temperature
=Scale factor of the universe



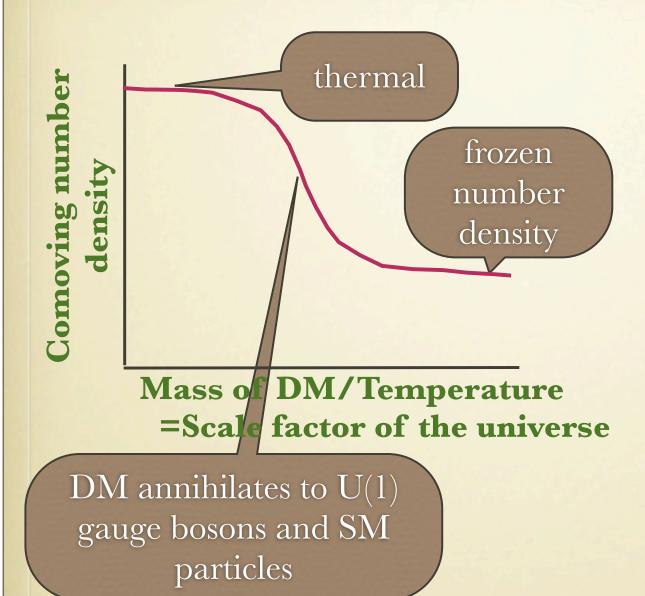
Mass of DM/Temperature
=Scale factor of the universe



DM annihilates to U(1) gauge bosons and SM particles

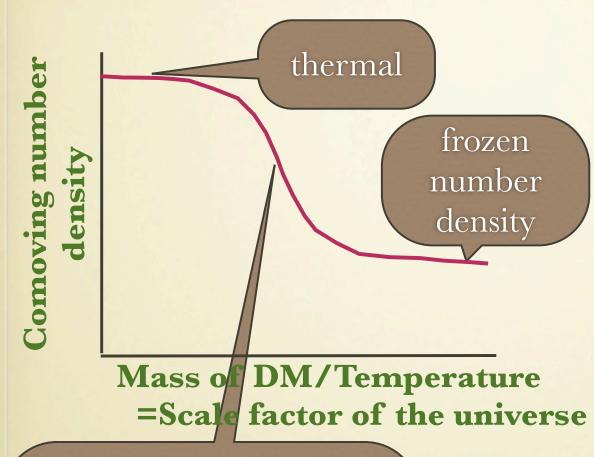


DM annihilates to U(1) gauge bosons and SM particles



energy density \propto

$$\frac{1}{\langle \sigma_{\rm ann} v \rangle} \propto \frac{m_X^2}{\alpha_X^2}$$



energy density \propto

$$\frac{1}{\langle \sigma_{\rm ann} v \rangle} \propto \frac{m_X^2}{\alpha_X^2}$$

Charge of X under

hidden U(1) is $\sqrt{4\pi\alpha_X}$

Charge of SM fermion f under

hidden U(1) is ϵeQ_f

DM annihilates to U(1) gauge bosons and SM particles

ANNIHILATION CROSS SECTION

Cross section changed by non-relativistic effects

$$\langle \sigma_{\rm an} v_{\rm rel} \rangle = k \frac{\pi \alpha_X^2}{m_X^2} S(m_\phi, m_X, v_{\rm rel})$$

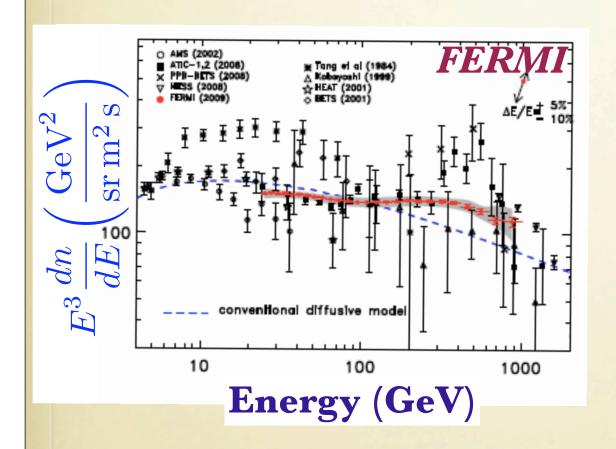
k ~ 1 depends on the spins of particles and other details

S is the "Sommerfeld enhancement" due to the attractive force between Xs that distorts the wave function at close separation.

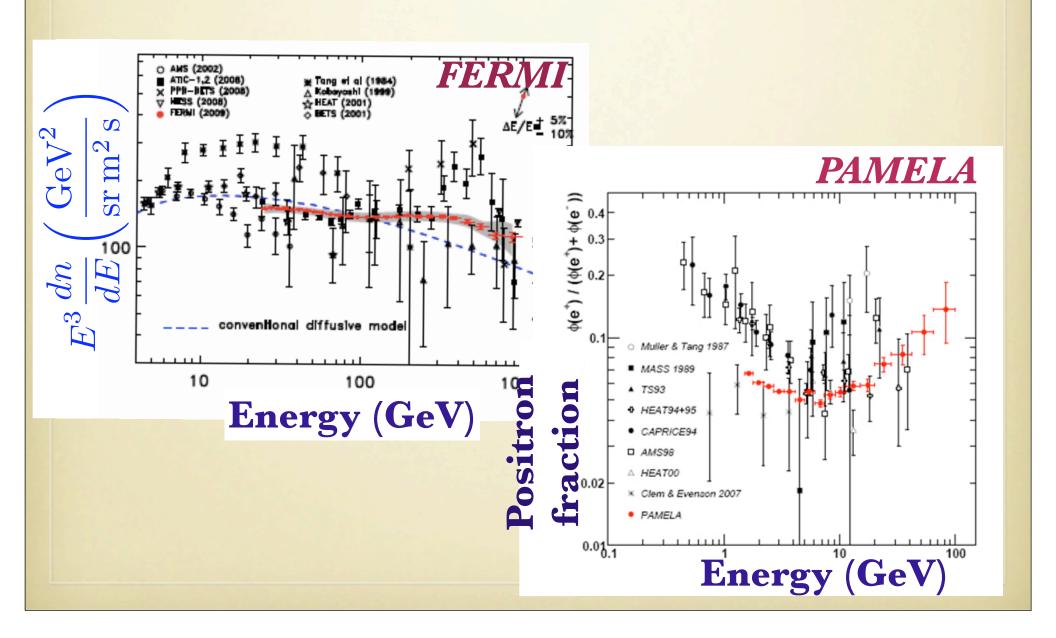
A. Sommerfeld, Annalen der Physik 403, 207 (1931)

Hisano, Matsumoto and Nojiri, PRD 67 (2003) 075014

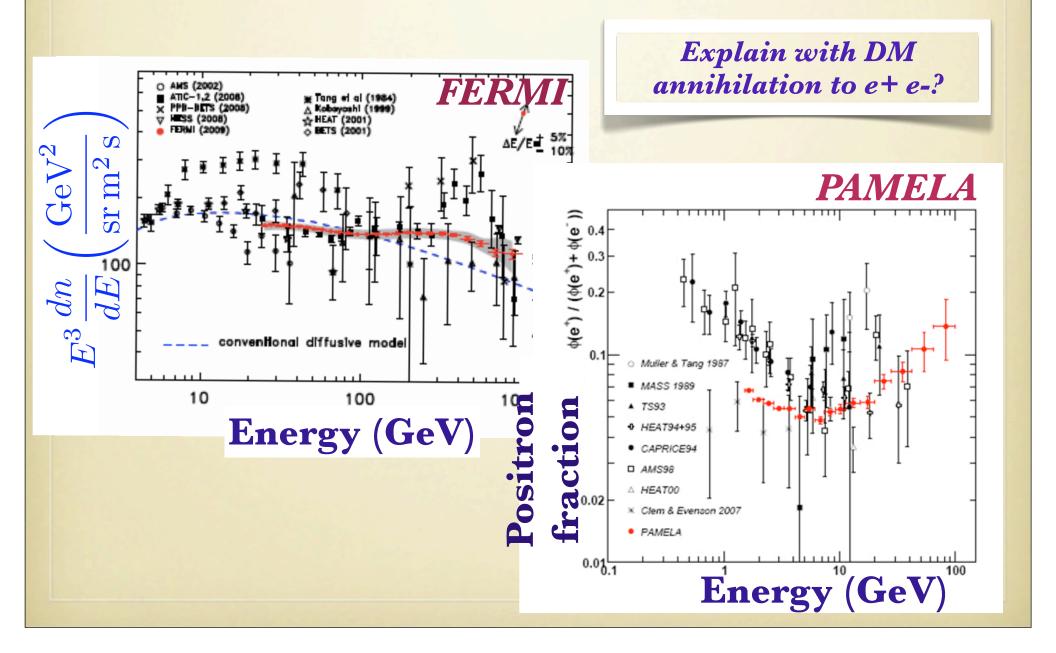
OBSERVATIONAL MOTIVATION: PAMELA AND FERMI EXCESSES



OBSERVATIONAL MOTIVATION: PAMELA AND FERMI EXCESSES



OBSERVATIONAL MOTIVATION: PAMELA AND FERMI EXCESSES



USE MASSIVE DARK FORCE CARRIER

$$\phi \rightarrow e^+e^ XX \rightarrow \phi\phi \rightarrow 2e^+2e^-$$

- Turns out the cross section required to explain PAMELA and Fermi is much larger than the typical weak scale cross section 3 x 10^(-26) cm^3/s
 - But S could be a 1000!
 - Use Sommerfeld enhancement get the right annihilation cross section in the halo to explain Pamela and Fermi.

Cirelli, Kadastik, Raidal and Strumia, Nucl. Phys. B 813, 1 (2009) Arkani-Hamed, Finkbeiner, Slatyer and Weiner, Phys. Rev. D 79, 015014 (2009)

- Away from resonances, the Sommerfeld effect depends on velocity
- This enhancement is saturated when velocity ~ force carrier mass/dark matter mass
- At resonance, the enhancement grows like

- Away from resonances, the Sommerfeld effect depends on velocity
- $S^{0} = \frac{\pi \alpha_{X}/v}{1 e^{-\pi \alpha_{X}/v}} \xrightarrow{\alpha_{X} \gg v} \frac{\pi \alpha_{X}}{v}$
- This enhancement is saturated when velocity ~ force carrier mass/dark matter mass
- At resonance, the enhancement grows like

 Away from resonances, the Sommerfeld effect depends on velocity

$$S^{0} = \frac{\pi \alpha_{X}/v}{1 - e^{-\pi \alpha_{X}/v}} \xrightarrow{\alpha_{X} \gg v} \frac{\pi \alpha_{X}}{v}$$

- This enhancement is saturated when velocity ~ force carrier mass/dark matter mass
- At resonance, the enhancement grows like

$$m_{\phi} \simeq \frac{6\alpha_X m_X}{\pi^2 n^2} , \quad n = 1, 2, 3 \dots$$

$$S \simeq \frac{\pi^2 \alpha_X m_\phi}{6m_X v^2} \ .$$

S. Cassel 2009 and T. Slatyer 2010

 Away from resonances, the Sommerfeld effect depends on velocity

$$S^{0} = \frac{\pi \alpha_{X}/v}{1 - e^{-\pi \alpha_{X}/v}} \xrightarrow{\alpha_{X} \gg v} \frac{\pi \alpha_{X}}{v}$$

 This enhancement is saturated when velocity ~ force carrier mass/dark matter mass

$$m_{\phi} \simeq \frac{6\alpha_X m_X}{\pi^2 n^2} \ , \quad n = 1, 2, 3 \dots$$

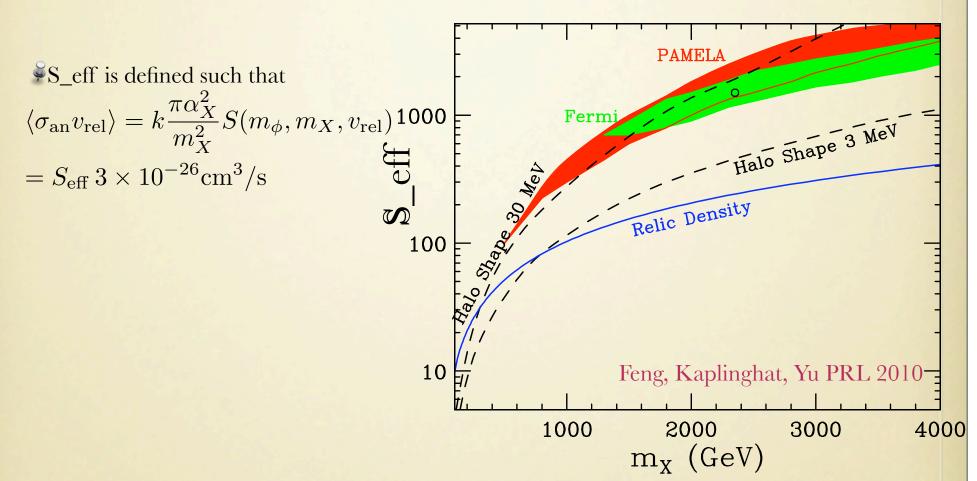
 At resonance, the enhancement grows like

$$rac{\pi^2 \alpha_X m_\phi}{6m_X v^2}$$
.

S. Cassel 2009 and T. Slatyer 2010

Large S enhancement requires large alpha. Can we still get the right relic density?

PAMELA/FERMI: DARK FORCE SOMMERFELD ENHANCEMENT EXPALATION



Fits from Bergstrom, Edsjo, Zaharijas PRL 2009 for 250 MeV dark force carrier

PAMELA/FERMI: DARK FORCE SOMMERFELD ENHANCEMENT EXPALATION

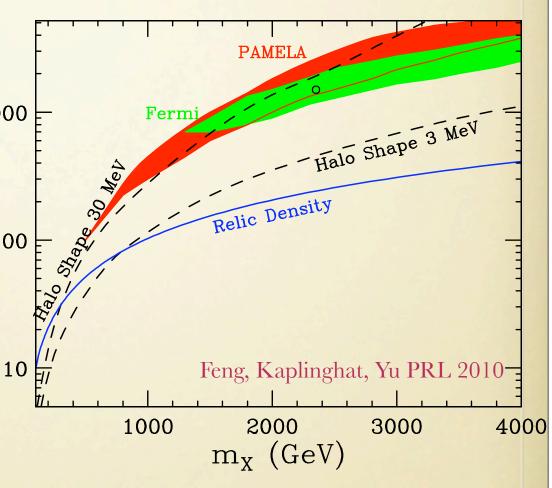
S_eff is defined such that $\langle \sigma_{\rm an} v_{\rm rel} \rangle = k \frac{\pi \alpha_X^2}{m_X^2} S(m_\phi, m_X, v_{\rm rel}) 1000$ $= S_{\rm eff} 3 \times 10^{-26} {\rm cm}^3/{\rm s}$

For the moment, neglect resonance ¹⁰⁰ and the fact that S>1 in the early universe.

To get the right relic density for mX~TeV, we need alphaX ~ 0.025

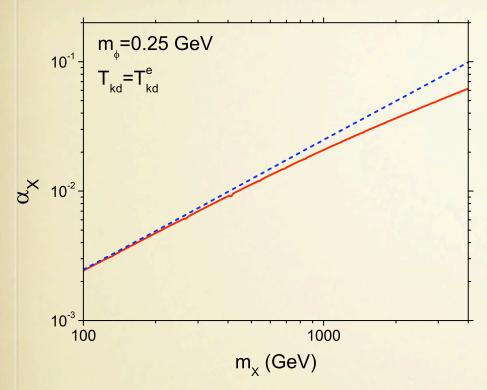
In the halo, $v \sim 10^{(-3)}$

Then $S\sim$ pi alpha/ $v\sim75$

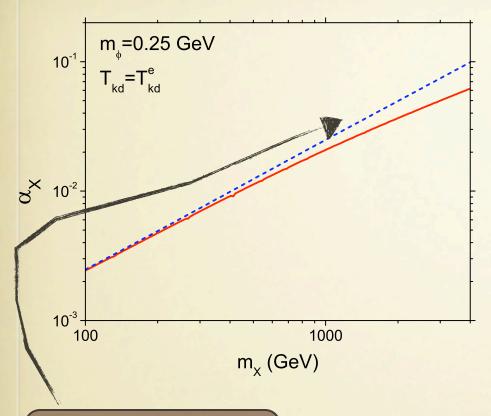


Fits from Bergstrom, Edsjo, Zaharijas PRL 2009 for 250 MeV dark force carrier

FREEZE OUT WITH SOMMERFELD ENHANCEMENT



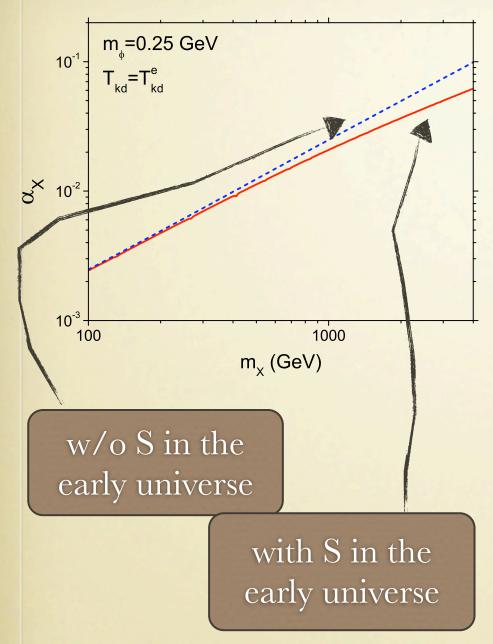
FREEZE OUT WITH SOMMERFELD ENHANCEMENT



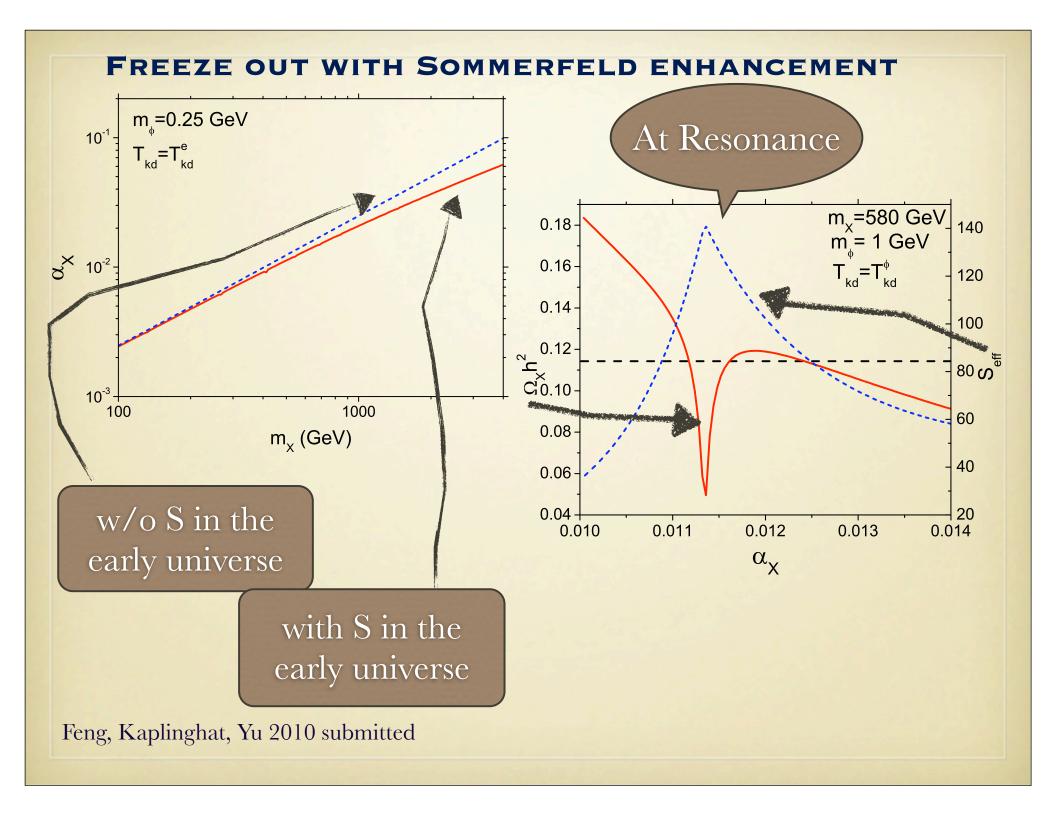
w/o S in the early universe

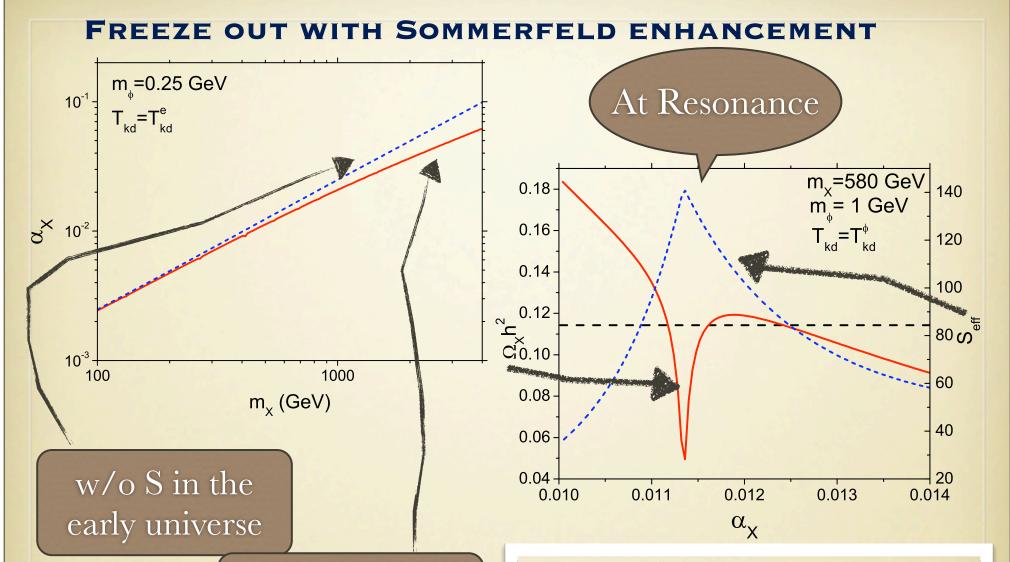
Feng, Kaplinghat, Yu 2010 submitted

FREEZE OUT WITH SOMMERFELD ENHANCEMENT



Feng, Kaplinghat, Yu 2010 submitted





with S in the early universe

Feng, Kaplinghat, Yu 2010 submitted

Annihilations happen until very late depleting dark matter. This is a major issue for regions close to resonance

FORCE CARRIER DECAYS

$$\phi \longrightarrow f \bar{f} \quad \tau_{\phi} = 6.8 \times 10^{-16} \text{ s} \left[\frac{4}{\sum Q^{2} N_{c}} \right] \left[\frac{10^{-3}}{\epsilon} \right]^{2} \left[\frac{E}{10 \text{ GeV}} \right] \left[\frac{1 \text{ GeV}}{m_{\phi}} \right]^{2}$$

$$\gamma f \longrightarrow \phi f \quad \sum_{f} n_{f} n_{\gamma} \langle \sigma v \rangle_{f\gamma} \sim w \frac{6}{\pi^{4}} \zeta(3)^{2} \pi \alpha_{\text{EM}}^{2} \epsilon^{2} T^{4}$$

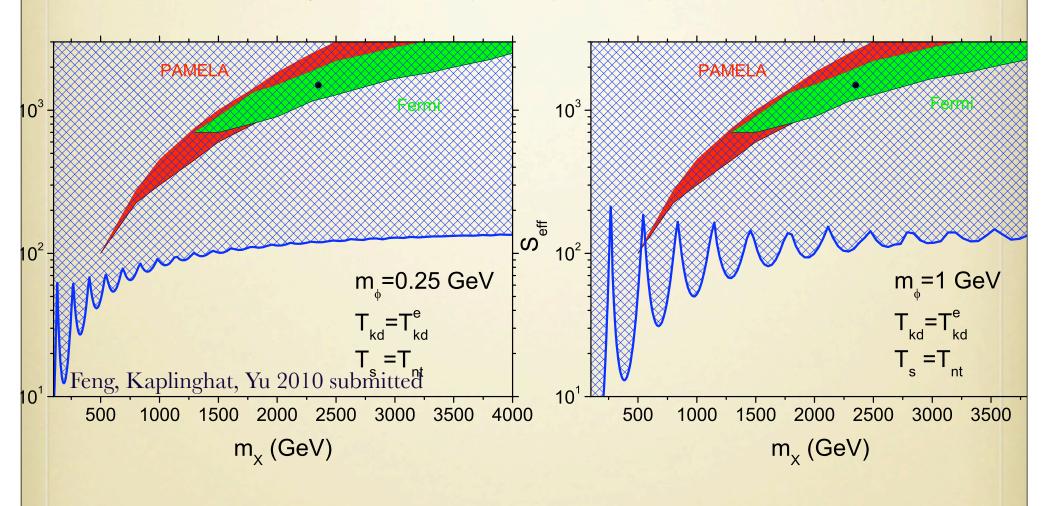
- Force carrier (phi) must necessarily decay to give rise to the positron excess
- Production of phi must outstrip the decay and the expansion rate

$$T \sim m_X/25$$

$$n_\phi/\tau_\phi < \sum_f n_f n_\gamma \langle \sigma v \rangle_{f\gamma}$$

$$m_X \gtrsim 100 m_\phi$$

MAXIMAL SOMMERFELD ENHANCEMENT



ASTROPHYSICAL UNCERTAINTIES

- Value of local density
 - Recent estimates suggest this to be 0.4 GeV/cm³ Catena and Ullio 09, Salucci et al 10
 - The best fit regions will shift down by (0.3/0.4)^2 if we use this central value
- Positrons from subhalos and substructure
- Propagation uncertainty, contribution from pulsars, etc

NON MINIMAL PARTICLE PHYSICS MODELS

- New annihilation channels
 - If phi mass is generated through Higgs mechanism, then generically Higgs is also light.

$$XX \to \phi h$$

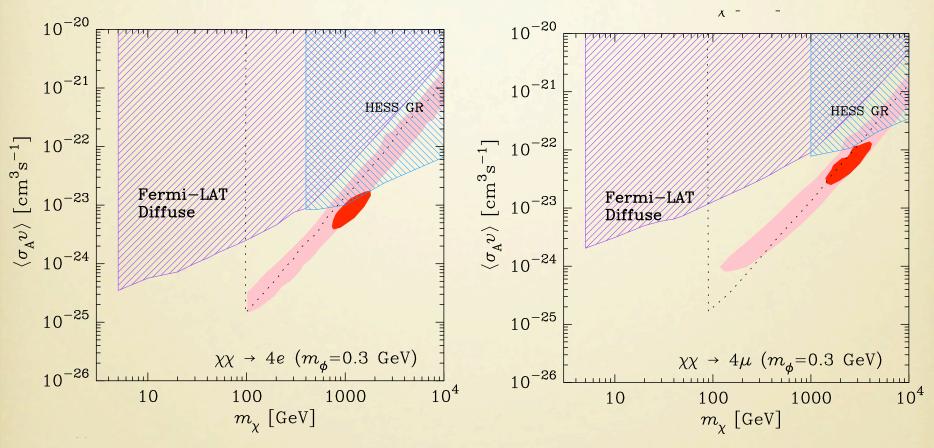
 $\langle \sigma_{\rm an} v \rangle = \frac{1}{4} \frac{\pi \alpha_X}{m_X^2}$

- Multi-state dark matter
 - Two stable states <u>with</u> each stable state split into two almost degenerate states
 Cholis and Weiner, 2010
- Non-abelian models, running of coupling
 Chen, Cline, Frey 09
 Zhang, Li, Cao, Li 09
 - Additional annihilation channels
 - Decay of higgs happens late after BBN

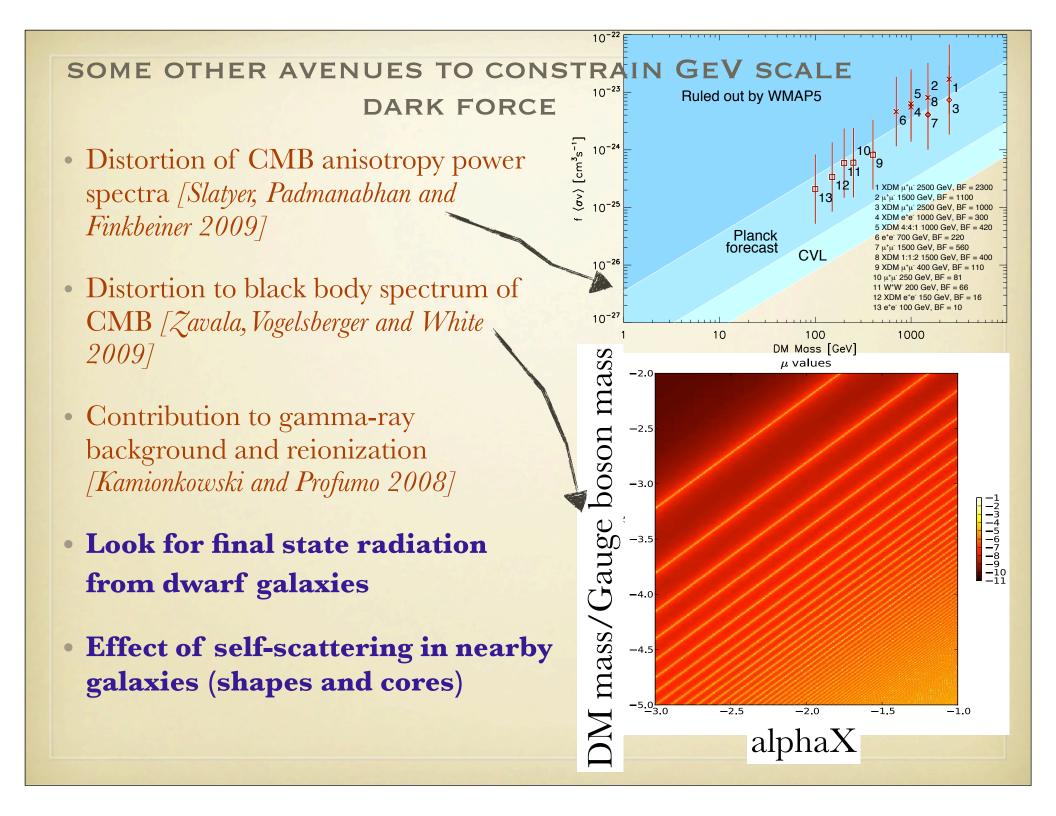
S ~ 100 sufficient if TeV state explains Fermi and 100 GeV state explains PAMELA

But no self consistent freeze out calculation

GALACTIC CONSTRAINTS



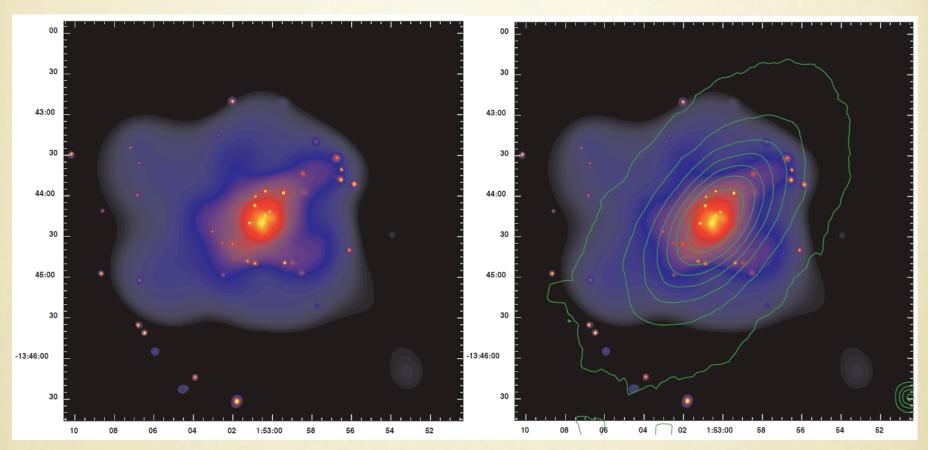
Meade, Papucci, Strumia, Volanksy 2009 Abazajian, Agarwal, Chacko, Kilic 2010



SCATTERING

- DM particles would interact with each other with a potential given by $V(r) = -\frac{\alpha}{r}e^{-m_{\phi}r}$
- Let a be such that $-V(a) = \frac{1}{2} \frac{m_X}{2} v_{\rm rel}^2$
- Then cross section $\sim \pi a^2 > \pi/m_\phi^2$
- Quantum effects change this cross section significantly [Buckley and Fox 2010]
- Effects in the late universe if $n_X \langle \sigma_{\text{scatter}} v_{\text{rel}} \rangle > (\text{age})^{-1}$
- Halos get spherical
- Cores in the density profile of halos

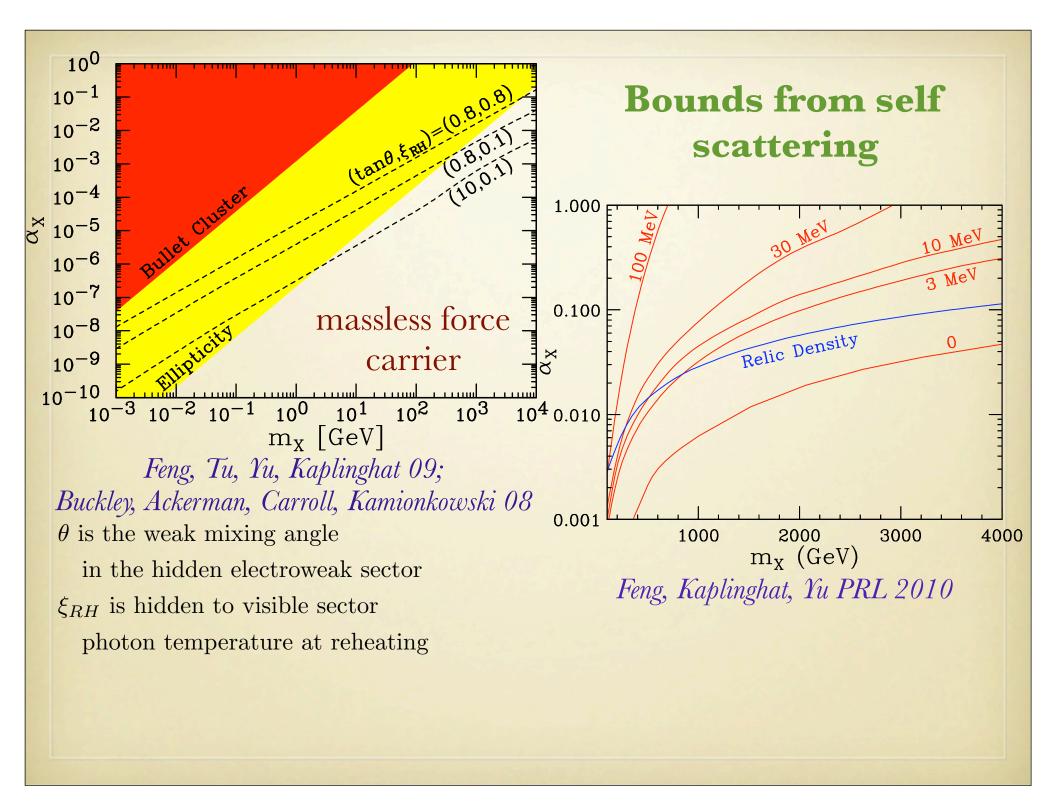
NGC 720 HAS AN ASPHERICAL DARK MATTER MASS DISTRIBUTION



Smoothed Chandra image at 06-10 keV

Overlaid with optical contours from DSS image

Buote, Jeltema, Canizares, Garmire 2002

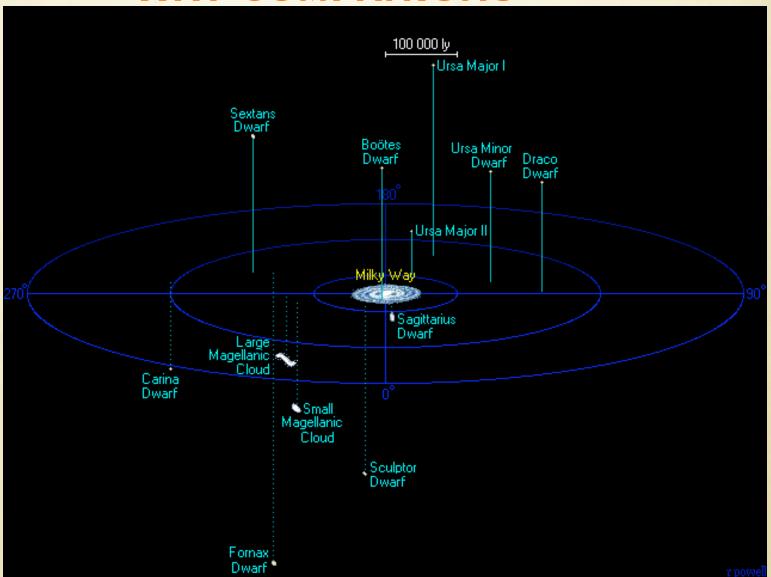


Local group (predictions from a simulation with cold dark matter)

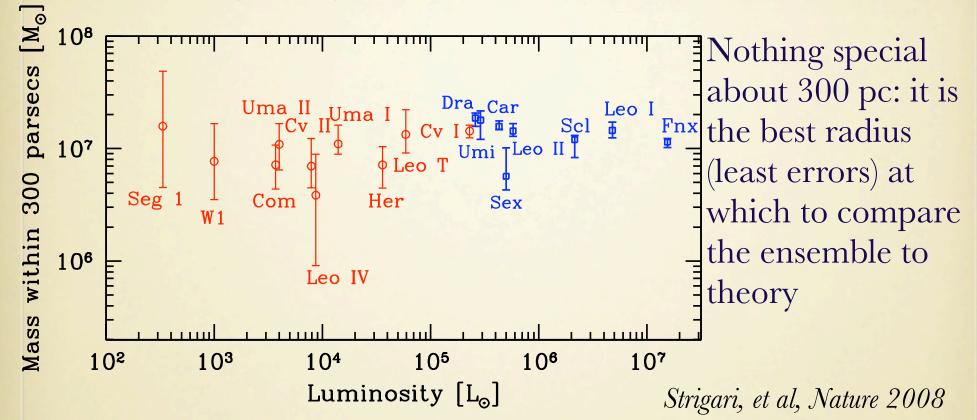
Via Lactea: Diemand et al 2006

PRE-SDSS (CLASSICAL) MILKY WAY COMPANIONS

Picture
without
the new
satellites
discovered
by Sloan
Digital Sky
Survey

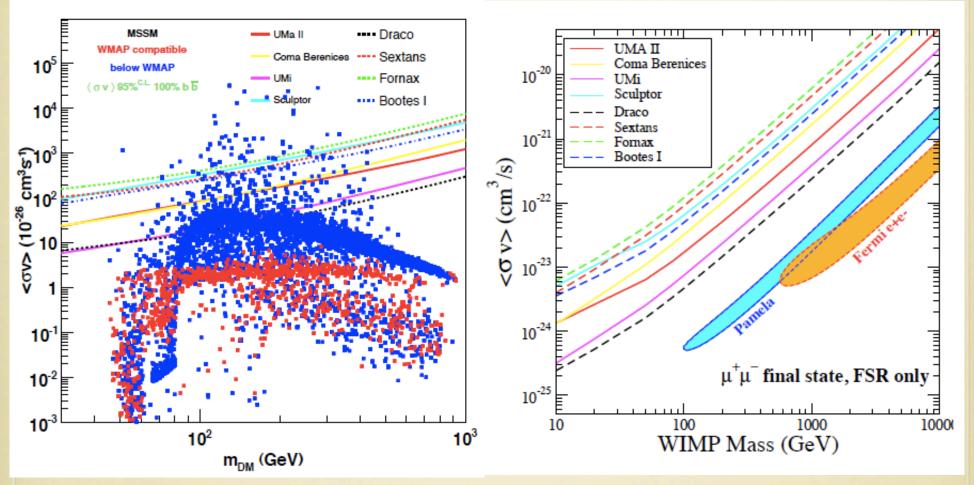


THE MILKY WAY COMPANIONS



- => Density = 0.1 Solar Mass / parsec^3
- => consistent with basic CDM predictions for objects that collapse early, z~10

GAMMA RAYS FROM DM ANNIHILATION IN THE SATELLITES: FERMI CONSTRAINTS

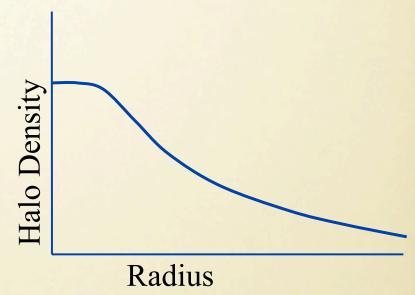


Fermi/LAT collaboration, Bullock, Kaplinghat, Martinez 2010

Does not include Segue 1, could be the best constraint

CORE OR CUSP?

- Canonical CDM
 simulations show that
 density of dark matter in a
 galactic halo increases with
 decreasing radius on
 observable scales. Is this
 the case observationally?
- Self-interactions, self-annihilations and finite primordial phase space density will all stop this increasing density with decreasing radius trend. But at what radius?



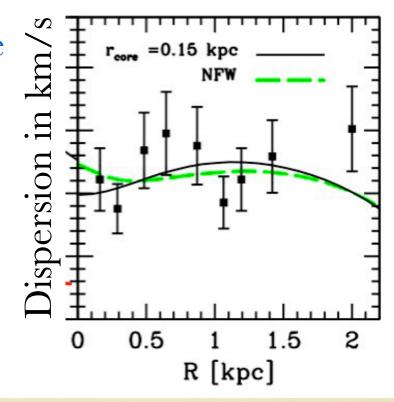
PROBLEM: WE CAN'T (YET) MEASURE THE SLOPE OF THE DENSITY PROFILE IN THE SATELLITES

- Standard way to measure density profiles is to look at velocity dispersion of the stars in these dwarfs. Velocity dispersion (temperature) tells us about the potential well.
- However, there is a fundamental degeneracy with the velocity dispersion anisotropy of stars that prevents one from measuring the profile well.

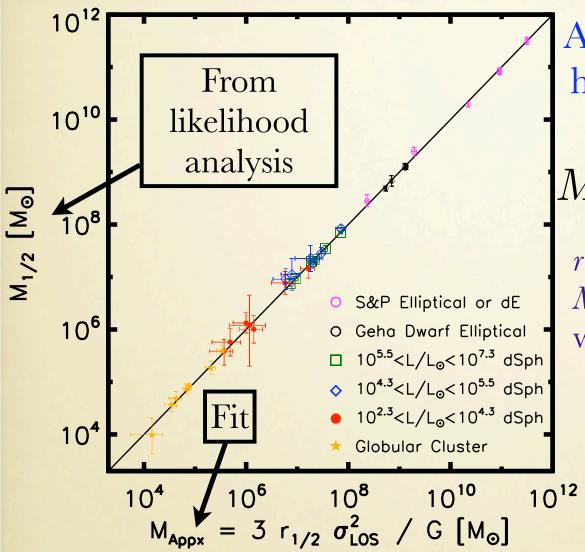
NFW density profile increases as 1/ radius close to the center, i.e., a **cusp**

Black curve are for cored density profile

Strigari et al 2006



WHAT CAN WE MEASURE IN THE SATELLITES?



Answer: Mass within the half-light radius of stars

$$M_{1/2} = \frac{3r_{1/2}\langle \sigma_{\text{LOS}}^2 \rangle}{G}$$

 $r_{1/2}$: 3D half-light radius $M_{1/2}$: dynamical mass within half-light radius

Wolf, Martinez, Bullock, Kaplinghat, Geha, Munoz, Simon, Avedo MNRAS 2010 Similar results from Walker, Mateo, Olszewski, Penarrubia, Evans, Gilmore ApJ 2009

Data from Wolf, Martinez, Bullock, Kaplinghat, Geha, Munoz, Simon, Avedo MNRAS 2010

$$M_{1/2} = \frac{3r_{1/2} \langle \sigma_{\text{LOS}}^2 \rangle}{G}$$

$$M_{1/2} = \frac{3r_{1/2} \langle \sigma_{\text{LOS}}^2 \rangle}{G}$$

Turn this into an average density within the stellar half light radius

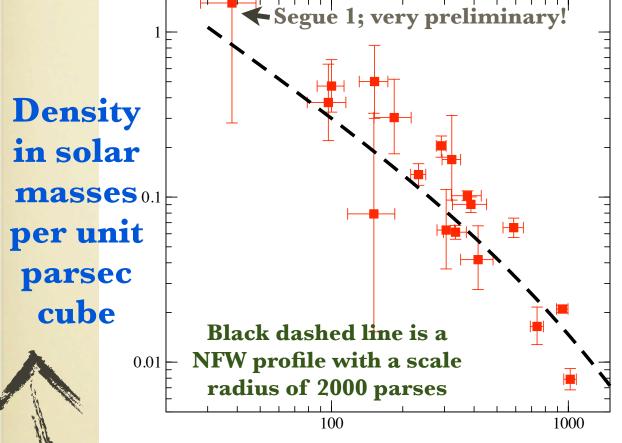
Density
in solar
masses
per unit
parsec
cube

$$M_{1/2} = \frac{3r_{1/2} \langle \sigma_{\text{LOS}}^2 \rangle}{G}$$

Turn this into an average density within the stellar half light radius



Data from Wolf, Martinez, Bullock, Kaplinghat, Geha, Munoz, Simon, Avedo MNRAS 2010



$$M_{1/2} = \frac{3r_{1/2}\langle \sigma_{\text{LOS}}^2 \rangle}{G}$$

Turn this into an average density within the stellar half light radius

Half light radius in parsec

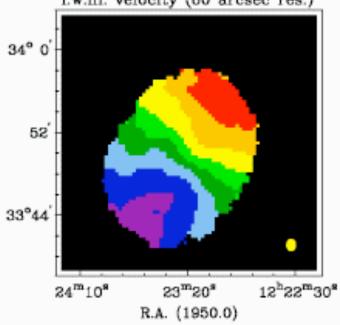
Data from Wolf, Martinez, Bullock, Kaplinghat, Geha, Munoz, Simon, Avedo MNRAS 2010

What about cores in larger galaxies, further away?

Rotation supported galaxies



12h22m30s 24^m10⁸ 23^m20^s I.w.m. velocity (60 arcsec res.)



Galaxy: UGC 7524 Distance: 4.3 Mpc .SAS9*. Type: 10.55

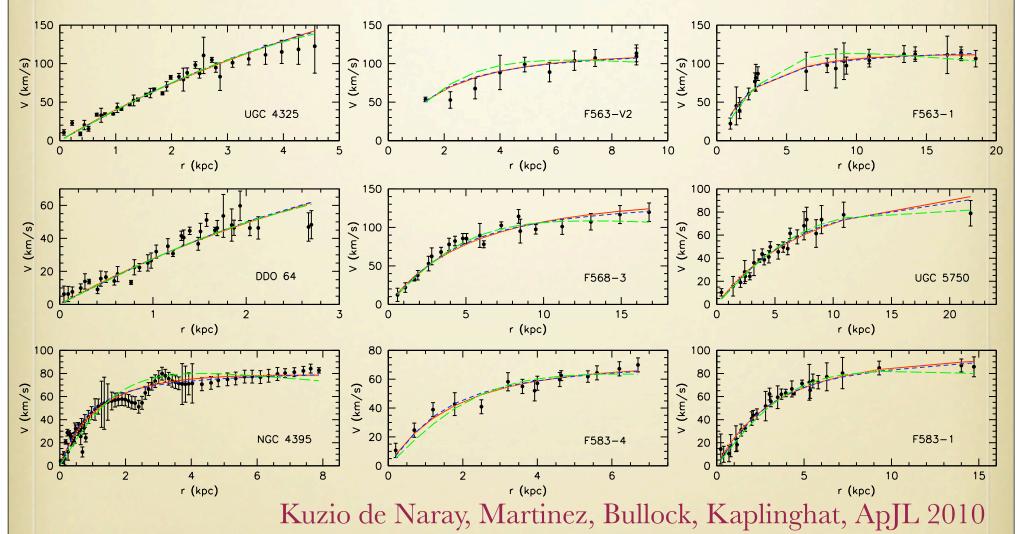
 34° Inclination: 13.'2 x 10.'8 Optical size:

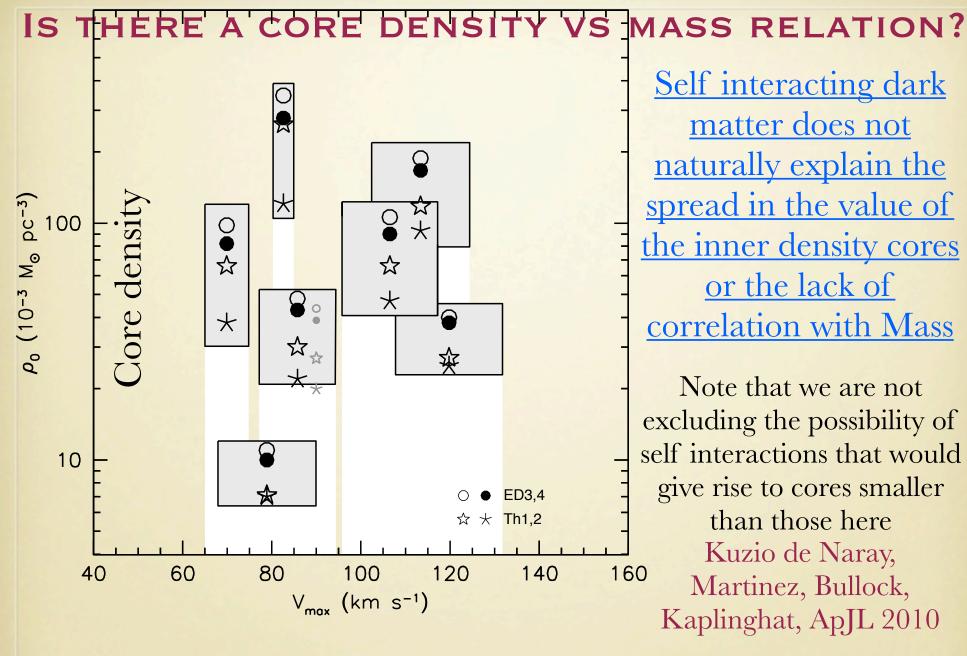
14.4 x 10⁸ M_☉ Total HI mass:

© WHISP, Mon May 26 15:57:00 1997

NEARBY LOW SURFACE BRIGHTNESS GALAXIES

Note the linear rise in rotation velocity at small radii for all galaxies => constant density cores





Self interacting dark matter does not naturally explain the spread in the value of the inner density cores or the lack of correlation with Mass

Note that we are not excluding the possibility of self interactions that would give rise to cores smaller than those here Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

CONCLUSIONS

- Sommerfeld enhanced explanations of PAMELA and Fermi electron and positron anomalies have not been shown to self-consistently explain the observed relic density
- The cores in LSBs are not naturally explained by selfinteractions of dark matter
- No evidence for cores or cusps in MW dSphs but that is the place to look for any deviations from collision less cold dark matter paradigm